KNF Techniques for Establishing and Confirming Uncertainties for CANDU Fuel Performance Analyses

Kang-Moon Lee
KEPCO Nuclear Fuel Company, 242 Daedeokdaero 989beon-gil, Yuseong-gu, Daejeon, Korea,
kmoonlee@knfc.co.kr

1. Introduction

There is an increasing interest in computational fuel performance analysis to replace the conservative evaluation model calculations by a quantitative uncertainty analysis. Important parameters of fuel rod performance, such as rod internal gas pressure, peak fuel centerline temperature, and cladding hoop strain are affected by several uncertainties from scatter of measured values, approximations of modelling, variation and imprecise knowledge of initial and boundary conditions. Their propagation through code calculations provides probability distributions and ranges for the code results.

This study is intended to assess the combined effects of uncertainties preliminarily by using a non-parametric order statistics approach [1]. In Uncertainty Analysis (UA), all potentially important uncertain parameters are identified and quantified in the uncertainty analysis of the in-house CANDU fuel performance code developed in KNF. The evaluation of the margin to acceptance criteria is based on the upper limit of the distribution for the calculated results.

2. Description of the UA Method

The UA method is the process developed to characterize the output variables affected by uncertainty.

2.1 Input Uncertainty Characterization

Uncertainty sources are identified, according to their origin, as follows:

- Code uncertainties
- Representation(i.e., nodalization) uncertainties
- Plant uncertainties, and
- User effects

2.2 Uncertainty Propagation

The error propagation occurs through the code is an ‘imperfect’ tool, as shown in Figure 1. In statistics methods, the uncertainties must characterize the range of variation of each parameter and the number of performed code runs is a function of the target (selected) level of confidence. Sample size selection is usually based on Wilks’ tolerance intervals (e.g., 124 runs for 3rd order one-sided 95%/95% tolerance limit) [2, 3]. The number of input uncertain parameters is not limited.

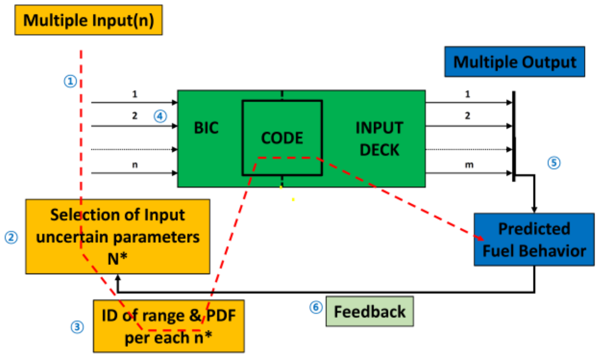

Figure 1. Uncertainty Propagation through the Code

2.3 Output Uncertainty Characterization

The results of the propagation of uncertainty are processed to get the most accurate possible picture about the uncertainty in the outputs. There is a large amount of numeric and graphic statistical tools available for performing this task. Statistical evaluations based on Spearman rank correlation coefficient [4] to determine the sensitivities of input parameter uncertainties on the uncertainties of key output parameter results are performed.

3. Applications of the UA Method

Seven basic steps for performing an uncertainty analysis for CANDU fuel performance analyses are developed and applied as shown in Figure 2.

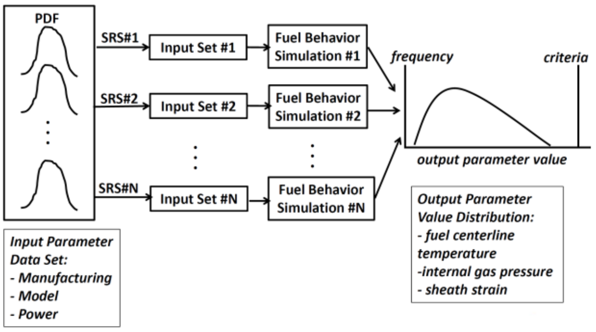

Figure 2. Fuel Performance Analysis Based on Non-parametric Order Statistics

3.1 Selection of the Nuclear Power Plant and Scenario

- Wolsong 2/3/4 CANDU 6 reactors
- Fuel performance under normal operating conditions

3.2 Input Characterization of the Scenario and Identification of Important Phenomena

- Manufacturing parameters; UO_2 density, diametral clearance, axial clearance, He fraction, grain size
- Model parameters for key fuel performance: rod internal gas pressure, peak fuel centerline temperature, and cladding hoop strain
- Operational parameters; element power-burnup history

3.3 Selection of the Code

- The in-house CANDU fuel-performance code under normal operating conditions qualified through verification & validation as per CSA Standard N286

3.4 Preparation and Qualification of the Input Deck

- By a qualified engineer and verification as per KNF QA procedure

3.5 Selection of the Uncertainty Method

- UA method (Wilks' formula) based on non-parametric order statistics

3.6 Application of the Uncertainty Method

- 3rd order tolerance limit/124 runs; Run Set #1(Reference Case), Run Set #2, Run Set #3
- 20th order tolerance limit/554 runs; Run Set #4
- Sensitivity analysis; Spearman rank correlation coefficient as sensitivity measure

3.7 Comparison of Results with the Relevant Criteria

- Rod internal gas pressure (P_{gas}), peak fuel centerline temperature ($T_{\text{¢}}^{UO2}$), and cladding hoop strain (ε_{sh}^{tot}) (Table 1)

Table 1. Summary of Uncertainty Analysis Results

Analysis Methodology	**Limiting Performance Parameter Value: 95% Uncertainty Limit**			
	$T_{\text{¢}}^{UO2}$ (°C)	P_{gas} (MPa)	ε_{sh}^{tot}(ridge) (%)	ε_{sh}^{tot}(mid) (%)
SRSS	1626	6.47	1.35	0.73
Run Set # 1 (124 Runs)	1559	3.26	0.99	0.41
Run Set # 2 (124 Runs)	1603	5.67	1.12	0.54
Run Set # 3 (124 Runs)	1602	3.48	0.90	0.42
Run Set # 4 (554 Runs)	1558	2.80	0.86	0.36

4. Result Summary

It is proposed that UA combining the various sources of uncertainty (i.e., manufacturing, model and power) in the key input parameters into an uncertainty in the key fuel performance output parameters (i.e., $T_{\text{¢}}^{UO2}$, P_{gas}, ε_{sh}^{tot}).

Four sets of simulation runs are performed: three 3rd order UA cases (124 runs) and one 20th order UA case (554 runs).

- The 95%/95% tolerance limits of key fuel performance output parameters meet the relevant acceptance criteria for all the four cases.
- The 95%/95% tolerance limits for the three 3rd order UA cases are different one another due to the random number set differences; and
- The 95%/95% tolerance limit for the 20th order UA case is lower than those for the 3rd order cases, and the result demonstrates the highest fuel performance margin.

A statistical sensitivity analysis using Spearman rank correlation coefficient has been performed to provide the importance of the respective input parameter uncertainty on key fuel performance output parameters (Figure 3).

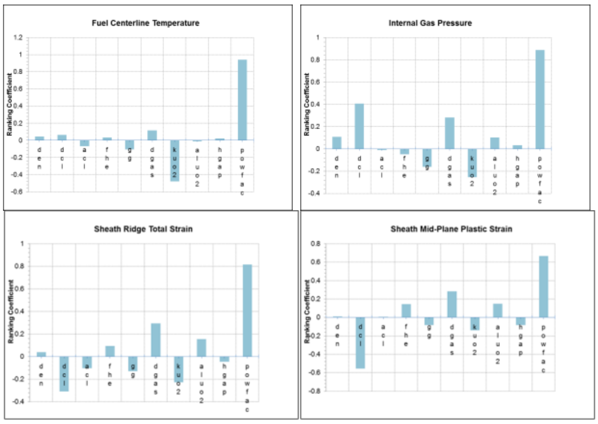

Figure 3. Sensitivity Analysis Results Based on Spearman Rank Correlation

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